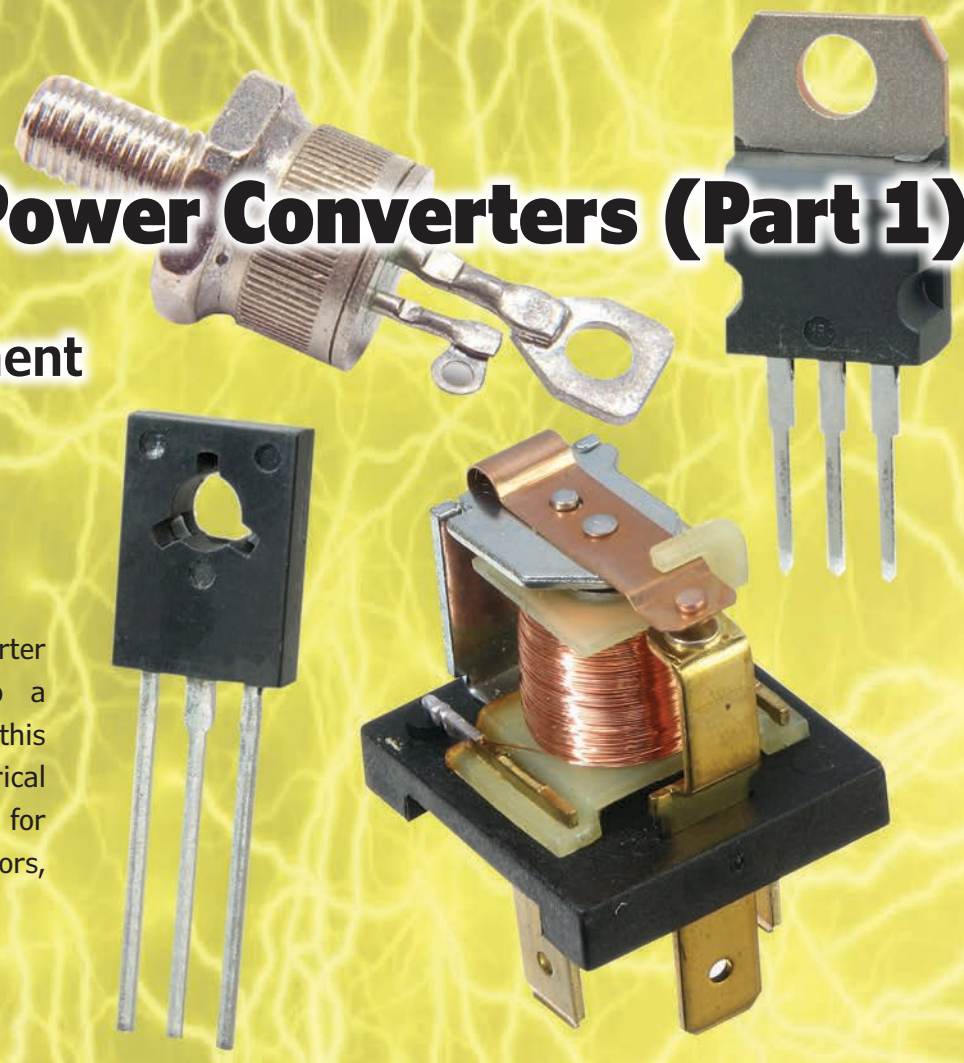
THE CONSUMMATE ENGINEER

Electrical Power Converters (Part 1)

Power Management

COLUMNS



An electrical power converter manages power delivery to a device such as a motor. In this article, George covers electrical power converters (AC or DC) for devices such as heaters, motors, and actuators.

By George Novacek

Most embedded controllers need a functional block control engineers call a power converter. It manages power delivery to a plant, the device, e.g. a motor, doing the actual work. The power can be derived from a fuel flow, or it can be electric, hydraulic, pneumatic, etc. Its delivery is modified in response to a small current from the controller. The plant is the power converter's load.

In this article, we'll discuss converters of electric power, AC or DC, for plants such as heaters, motors, actuators, and many other electrical devices. Common AC power sources deliver 115, 230, and 380 V at 50 Hz, 60 Hz, 400 Hz, and up to about 720 Hz from variable frequency generators (single phase, split-phase, or three-phase). Common DC sources are 3.3, 5, 12, 24, and 48 $V_{NOMINAL}$. Industrial loads can require thousands of volts and amps.

SAFETY FIRST

First, remember that voltages over about 48 V, AC or DC, even with a relatively low current capability, can be lethal. Therefore, many designs include a mandatory safety switch, which is an independent hard contact to safely remove power from the system. Solid-state switches, as well as all switches with a snubber, may have sufficient leakage to be dangerous.

Consider **Figure 1**. The safety switch must have no snubber and, therefore, should be operated when the load has been previously switched off (by the relay in this case) only. A snubber would thwart the required isolation from the power source.

RELAYS

The oldest and the simplest power converter is a relay. (Solid-state relays will be addressed later.) In Figure 1 the relay has a DC coil, which is convenient for embedded controllers, although many types of coils are available. Unlike solid-state switches often requiring a heat sink to keep their junction temperature within safe limits, relay contacts, due to low resistance, dissipate very little heat.

Almost all the heat dissipated by a relay comes from its coil, which, however, may

draw too much power for a given design. This can be remedied by the arrangement also shown in Figure 1. While the relay is not energized, capacitor C1 is charged to store enough energy for the solenoid to close the contacts once driven by transistor Q1. Then the coil current drops to the level determined by resistor R1, just enough to maintain the contacts closed. For example, Omron G2RS relays with a 12 VDC-rated coil close their contacts when energized by 75% (9.0 V) of their rated voltage and will drop out at 15% (1.8 VDC) of their rated voltage. Even less energy demanding but costlier and more prone to a mechanical failure are relays with a ratchet requiring just a current pulse to change state.

In general, switching or controlling DC loads is straightforward. It can be accomplished by many discrete semiconductors, including power amplifiers, which we'll discuss later. Hard contacts as well as solid-state devices need to be protected against the back-EMF kick caused by abruptly removing (i.e., with high di/dt ratio) the current flowing through the inductive component of the load. A freewheeling diode D1 across the relay coil in Figure 1 or a snubber R2C2 will do the job. For switching low voltages many ICs, such as Toshiba's TCK line of load switches, comprising integral thermal, overcurrent, overvoltage and other protection are available. It is often advantageous to use those ICs instead of discrete components[1] to lower component count and improve reliability.

Switching AC loads with relays has one serious shortcoming. Relays are too slow responding, 30 ms typically, to be synchronized with zero crossing of the AC power wave. Consequently, they turn the load on or off anywhere on the wave, causing unpredictable transients. These may result in contacts-damaging arcing and electromagnetic interference (EMI). Since all loads have some inductive component due to at least the wiring self-inductance, this problem must be addressed. The EMI can affect the nearby electronic equipment and sometimes violate national regulations. Snubbers and freewheeling diodes suppress the interference to some degree, but for some applications, the remnant spikes may still be unacceptable.

SILICONE CONTROLLED RECTIFIERS

Silicone controlled rectifiers (SCR), also called thyristors, are widely used solid-state switches. Some prefer to call only the high-power SCRs thyristors, but they are the same semiconductor components, so I'll use both names. **Figure 2a** shows the basic diagram

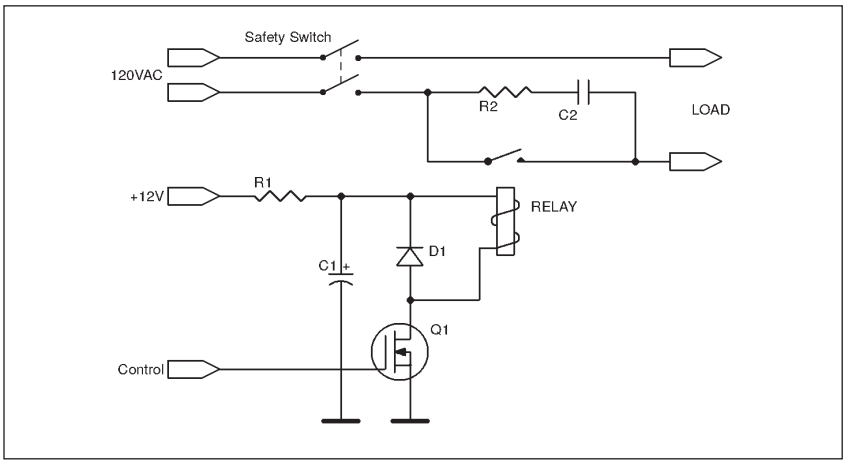


FIGURE 1
Energizing a load by a relay

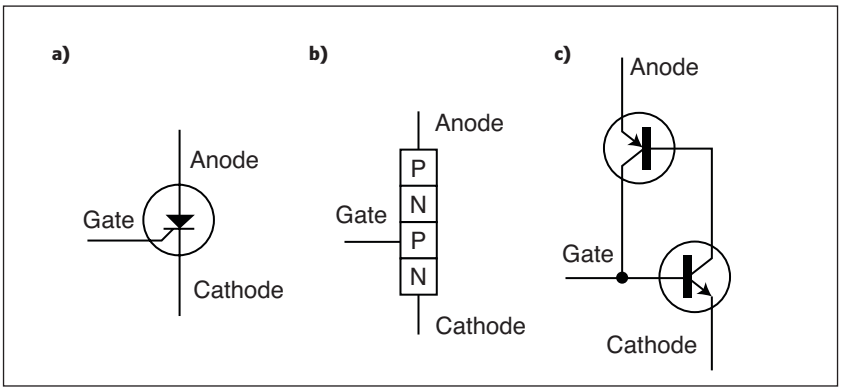


FIGURE 2
This is a Silicone Controlled Rectifier (SCR). Here you can see: **(a)** the basic diagram symbol, **(b)** the SCR's four-junction structure, and **(c)** an equivalent transistor topology showing that the SCR can be modeled with two complementary transistors.

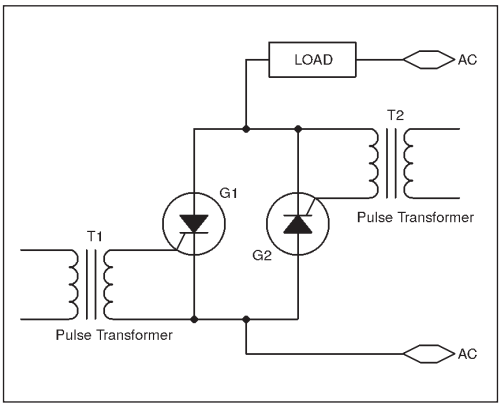


FIGURE 3
Back-to-back SCRs to supply full wave to the load

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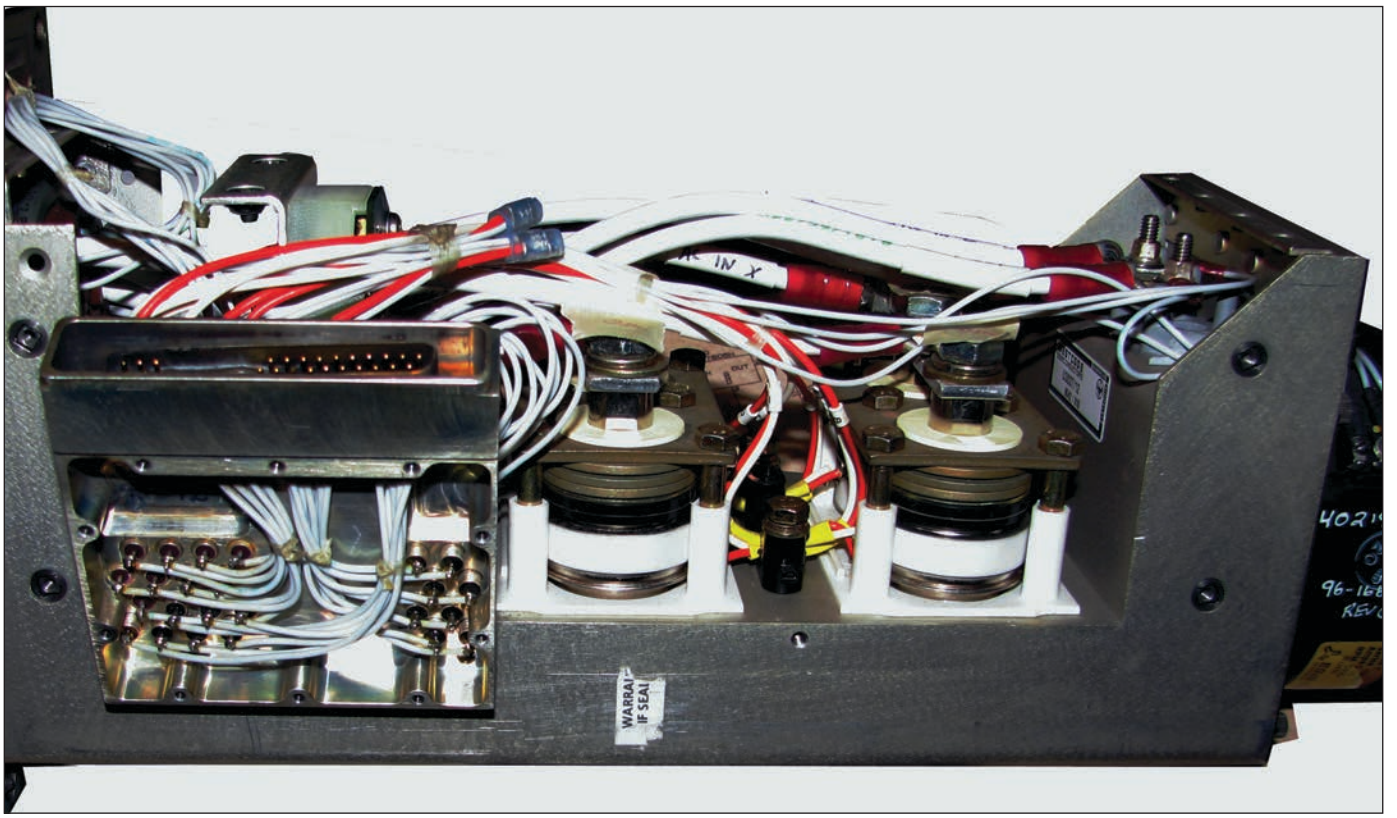

PHOTO 1
Power converter chassis for a three-phase heater with thyristor pairs.

symbol, while Figure 2b depicts the SCR's four-junction structure. Figure 2c is an equivalent transistor topology demonstrating that the SCR can be modeled with two complementary transistors.

A pulse or a voltage at the gate electrode, positive with the reference to the cathode, will trigger the SCR into conduction. The SCR will continue to conduct as long as the current flowing through it is larger than its holding current I_H. To turn the SCR off, its forward current must drop below the holding level. This can be achieved by removing the positive voltage from the anode by opening the circuit or by shorting the anode to the cathode. In AC operations, the turn-off happens automatically when the AC voltage enters its negative half wave. There are SCRs with a gate which can turn them off. We'll introduce them in the third part of this article series.

SCR, as its name implies, is a rectifier and, therefore, conducts current in one direction only. But because of its high reverse voltage capability, unlike most other semiconductors, two SCRs can be wired back-to-back (see **Figure 3** and **Photo 1**) and used to control AC loads. There are many ways to trigger an SCR. When isolation from the power source is needed, pulse transformers or optoisolators are used. When isolation is not an issue, other circuits can trigger the SCR.

Figure 4 is an example of opto-SCRs triggering thyristors. This is also the basic structure of solid-state relays (SSR). Resistor R1 limits the LED current, while R2 and R3 between the gate and the cathode of the respective thyristors improve their dV/dt characteristic and decrease the turn off time.

TRIACs

TRIACs are essentially two back-to back SCRs within one package and one common gate lead to eliminate complex triggering

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SOURCE

TCK106AF/107AF/108AF Load switch ICs
Toshiba | http://toshiba.semicon-storage.com

of the back-to-back SCRs for AC switching. **Figure 5a** depicts a TRIAC. Unlike SCRs which can only be triggered when the anode and the gate are positive with respect to the cathode, TRIACs can be triggered in all four quadrants, which means the gate can have any polarity with respect to Main Terminal 1 (MT1) (see Figure 5b). Triggering characteristics differ depending on which quadrant is used.

TRIACs are available for switching relatively low AC power only. Their maximum current rating is about 40 A. When compared with thyristors, TRIACs have relatively low tolerance for dV/dt. Littlefuse, STMicroelectronics, and others make alternistors, which are specially formulated TRIACs to exhibit dV/dt comparable to SCRs and, therefore, perform better with inductive loads than the TRIACs do. Unlike TRIACs, alternistors cannot be triggered in Quadrant IV, which is, in general, rarely used anyway. We'll discuss TRIACs in more detail in the second part of this article series. But for high-current, inductive loads switching, you will have to fall back on the back-to-back thyristors.

SNUBBERS

All hard contact and solid-state switches are sensitive to the dV/dt, which is the rate of change of the voltage across the switch. Arcing can result with contacts. Due to the internal parasitic capacitances in semiconductors, if the maximum specified dV/dt is exceeded, the device can trigger itself. Therefore, we need a snubber, such as R2-C2 in Figure 1. The cause of the dV/dt exceedance is, once again, the load inductance. Snubbers may be avoided by switching the loads at zero crossing. (Refer to the second article in this series.)

There are several methods for calculating the values of the R2 and C2 of the snubber. Needless to say, the characteristics of the load—and especially its inductance which includes wiring's parasitic inductance—play an important role. (Refer to the wiring inductance calculator at www.eeweb.com/toolbox/parallel-wire-inductance.)

Several methods for computing snubbers can be found in Resources section of this article. They all make it clear that the value of the snubber capacitor C depends very much on the inductance of the load, which is, by necessity, often just an estimate. The calculations will put you in the ballpark, but be prepared for some trial and error to achieve the best performance.

In the next part of this series we'll discuss TRIAC and thyristor applications in phase control, zero crossing triggering, and other solid-state switches commonly used to control high power.

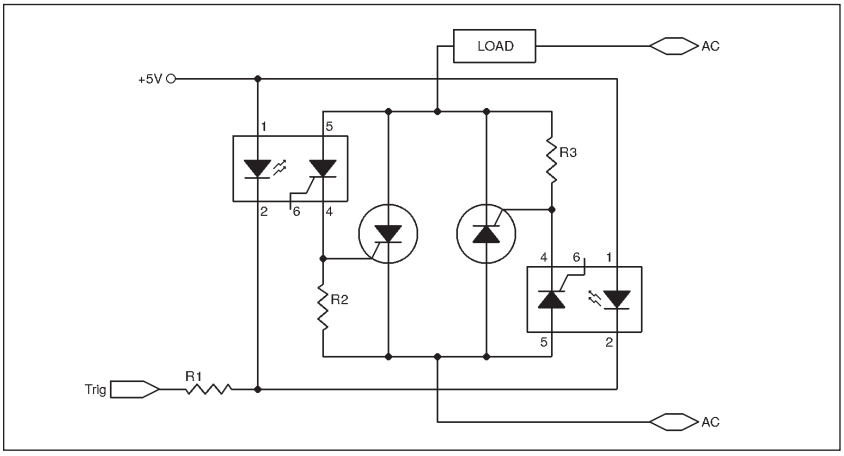

FIGURE 4
Triggering back-to-back thyristors by optically isolated SCRs

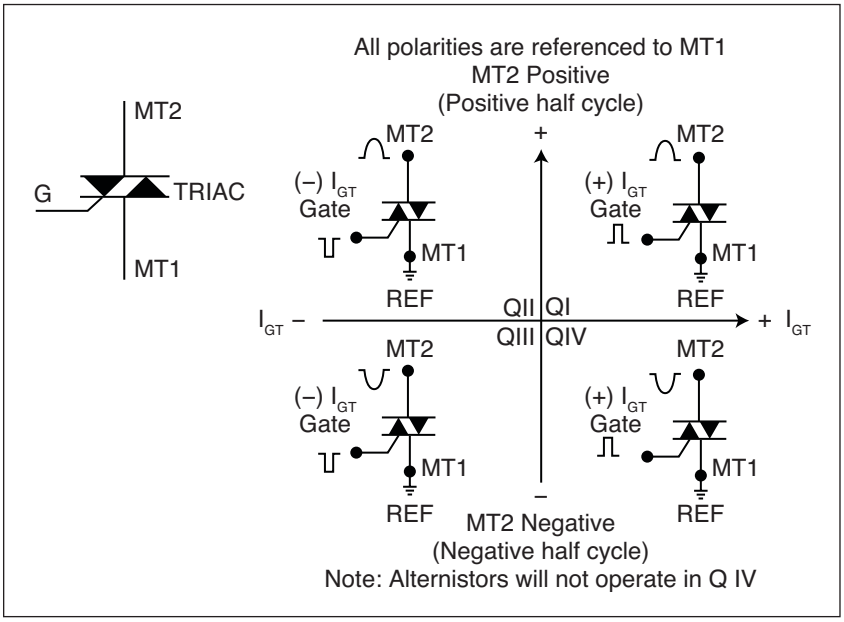

FIGURE 5
TRIACs can be triggered in all four quadrants

ABOUT THE AUTHOR

George Novacek is a professional engineer with a degree in Cybernetics and Closed-Loop Control. Now retired, he was most recently president of a multinational manufacturer for embedded control systems for aerospace applications. George wrote 26 feature articles for *Circuit Cellar* between 1999 and 2004. Contact him at gnovacek@nexicom.net with "Circuit Cellar"in the subject line.

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Electrical Power Converters (Part 2)

TRIAC and Thyristor Applications

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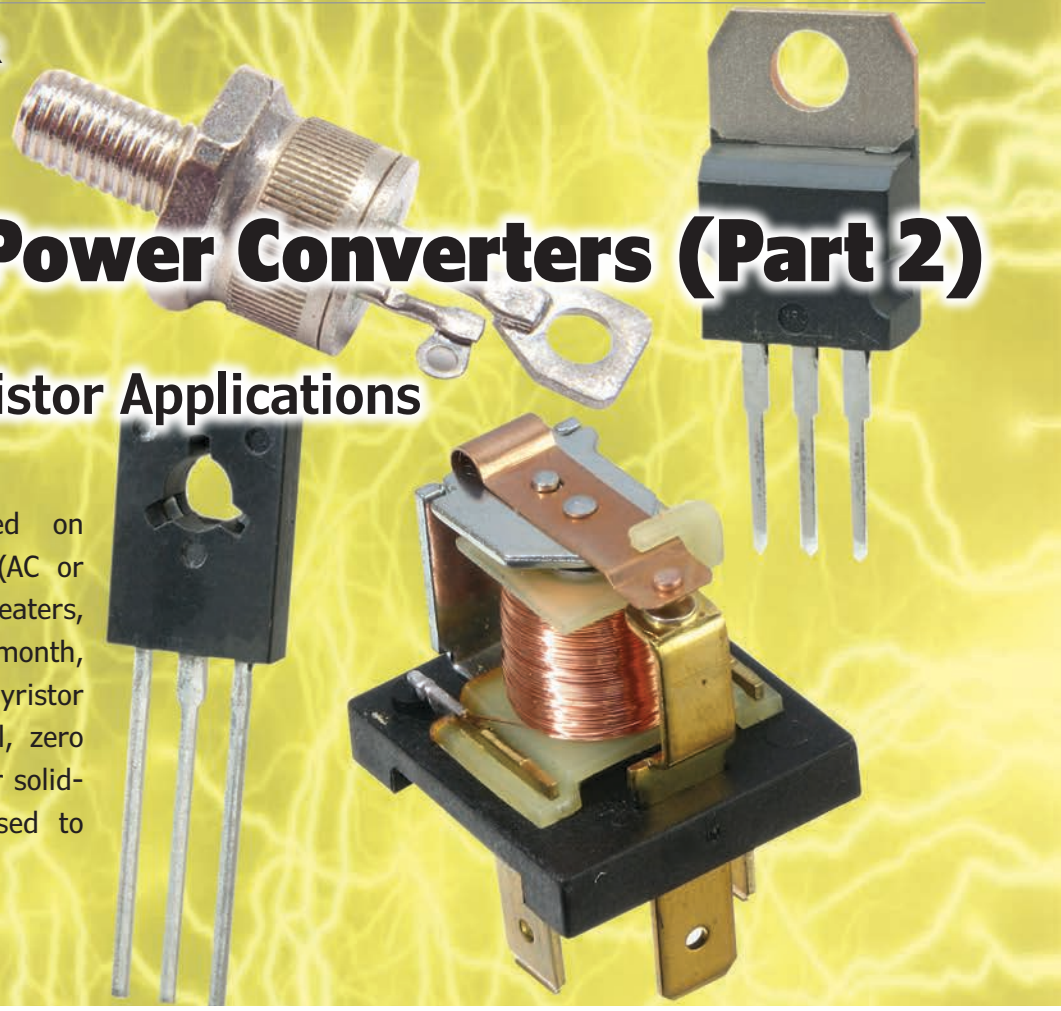

Last time, George focused on electrical power converters (AC or DC) for devices such as heaters, motors, and actuators. This month, George covers TRIAC and thyristor applications in phase control, zero crossing triggering, and other solid-state switches commonly used to control high power.

By George Novacek

There are two basic methods for silicon-controlled rectifiers (SCRs) and TRIACs to modify AC power. They can vary the firing phase angle or change the duty cycle. Both methods have their advantages and disadvantages. A light dimmer is a classic example of phase control. However, the same principle can be used to control heaters, motors, and other devices. Phase control is performed by leading- or trailing-edge techniques. **Figure 1** shows a typical topology of a leading-edge dimmer. Trailing-edge dimmers do not use SCRs or TRIACs. We'll discuss them in the third part of this article series.

CONTROL

Manual control of a dimmer is accomplished by potentiometer R1. In automatic control systems, the firing angle is modified by appropriate circuits, usually microcontroller based. Triggering SCRs and TRIACs at different phases of the input AC sinewave changes the average voltage across the load. The device is triggered some time after zero crossing of the input voltage depending on the phase lag caused by the R1C1 time constant. Capacitor C1 is charged through potentiometer R1. When its voltage exceeds the breakdown voltage of the DIAC, C1 is discharged into the TRIAC's gate, thus triggering it. Depending on the firing phase angle only a fraction of the sinewave becomes available to the load. **Figure 2** is the waveform at 60° firing angle. Considering the necessary triggering voltage plus the DIAC voltage drop, the average output power is always less than 100%.

Incandescent lights are notorious for their high inrush current upon turn-on. Inductor L serves to reduce that large initial spike referred to as di/dt. Typically, inductor L is about 100 µH and also helps to reduce electromagnetic interference (EMI) caused by the switching spikes.

The DIAC resembles two back-to-back Zener diodes. DIACs are available in the range of about 7- to 340-V breakdown voltage. A similar component called Sidac has greater voltage and current range. When the DIAC becomes conductive, it triggers the TRIAC in quadrants QI and QIII. A device called Quadrac incorporates the DIAC and the TRIAC in one package, thus reducing the parts count for assembly as well as improving reliability of the leading-edge phase control circuit. For speed control of motors, only a fraction, usually about 30%, of the phase control range can be utilized before the motors stall.

Switching the load at various angles along the power wave generates transients causing electromagnetic interference, which may not always be possible to suppress to a required level, especially with inductive loads. The

remedy in such situations may be the zero-crossing switching accompanied by the duty cycle (PWM) control.

REDUCE SWITCHING TRANSIENTS

To understand how zero-crossing switching reduces switching transients, consider **Figure 3**. The principle is simple: fire an SCR or a TRIAC driving a resistive load when the voltage wave (in this example, 120 V_{RMS}, the red trace) and the current wave (70 A_{RMS}, the green trace) are crossing zero at the same time. The device will conduct for the half cycle and then turn itself off automatically when the voltage and the current cross zero again. Therefore, at the switching points, there is no voltage, no current, and, thus, no transients.

The average power delivered to the load is then proportional to the duration of the burst of half cycles the TRIAC or the SCR conduct. However, the load must have a large time constant compared to the power frequency to integrate the power bursts for smooth operation. Unfortunately, the reality is not that simple. Consider a purely resistive load as illustrated by the red and green traces. Here, the voltage and the current cross zero at the same instant. Assume we're working with thyristor IRKT.91, switching 70 A_{RMS} current. The load resistance is, then, R_{LOAD} = 120 V/70 A = 1.71 Ω. IRKT.91has maximum holding current I_H = 200 mA and latching current I_L = 400 mA.

The holding current I_H for thyristors, TRIACs, and other semiconductor switching devices is the minimum current that must flow through the device to continue to conduct—that is, to stay on after having been triggered. When the current drops below the holding (also called hypostatic) level, the device turns off. The latching current, I_L, must make up for any missing input gate current, such as when the device is triggered by gate pulses, to keep it conducting. In other words, it must keep the internal structure of the device latched. I_L is always higher than I_H, often significantly. In the case of IRKT.91, it is twice the I_H—that is, 400 mA. In addition, like with all semiconductor devices, there needs to be some minimum forward voltage across the PN and NP junctions of the switching device for the forward current IF to flow. The minimum forward voltage is specified for every device at a specific forward current IF, and it is typically about 1.5 V.

This means that the IRKT.91 thyristor will not turn on at 0 V at its anode, but it will need a minimum of about 1.5 V between the anode and the cathode to fire. In addition, IF of at least 400 mA must flow through the device which means the voltage drop across the load must be added. As a consequence, the thyristor

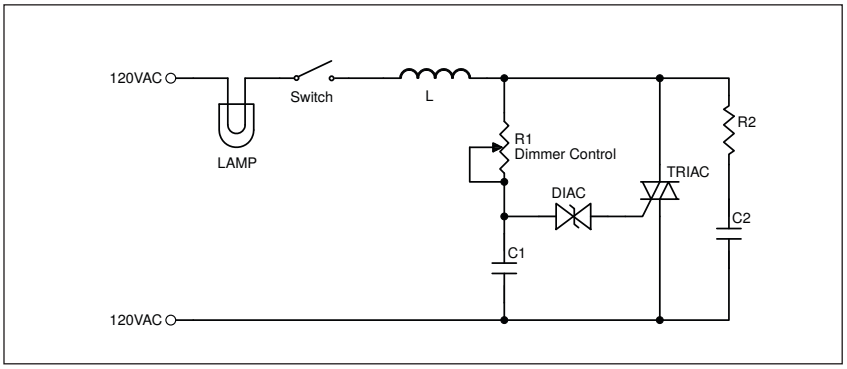

FIGURE 1
A light dimmer with a snubber circuit

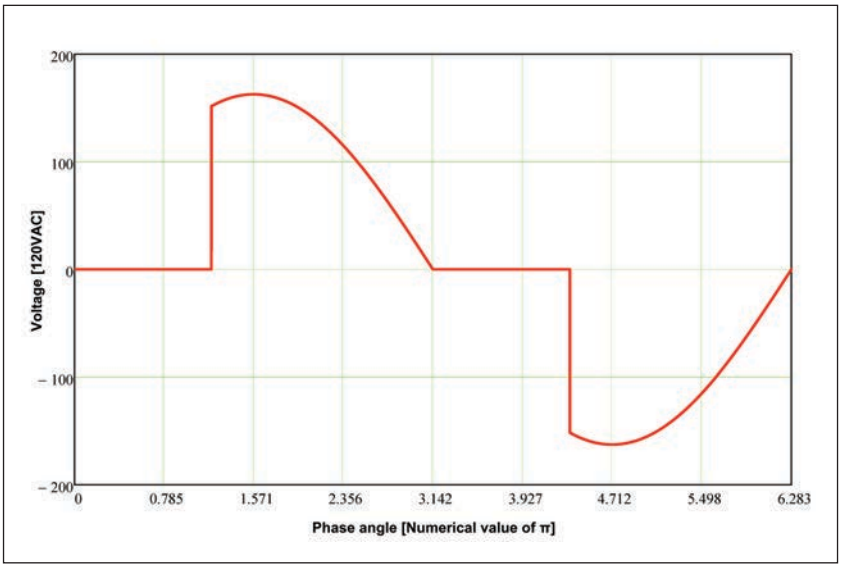

FIGURE 2
Leading edge phase controlled one period of voltage waveform delivered to the load

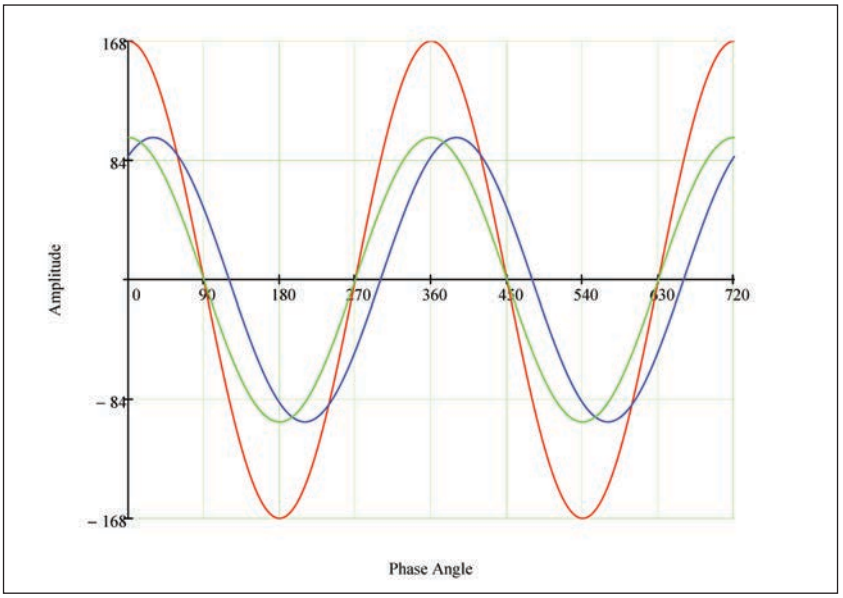

FIGURE 3
Switching at zero crossing. Voltage is red, current is green and blue trace.

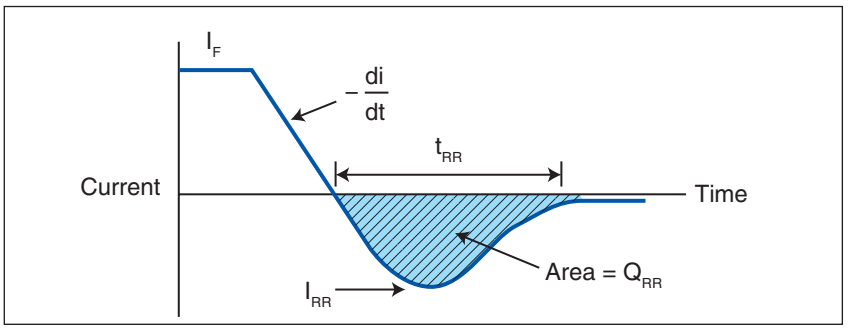

FIGURE 4
Thyristor current during device turn-off. Notice the delay when the current flows in reverse polarity

will fire at approximately 2.2 V of the power wave. Furthermore, the thyristor won't turn off when the forward current IF drops below the latching current as one might expect. Due to the internal mechanisms, the thyristor will disconnect, especially at higher frequencies and currents, significantly later. This is illustrated in **Figure 4**. To turn the device off, the forward current must drop below the holding level I_H at which point the thyristor control junction needs to recover its blocking state before a forward voltage can be reapplied without conduction. If you imagine a sine wave being switched to a load, the forward (anode) current is driven into reverse and a negative current flows. This permits charge movement within the PN layers and allows the two outer junctions to block any further reverse current after the stored charge, due to the presence of current carriers in the junction region has been recovered. The delay before the forward voltage can be re-applied is typically between 10 and 100 µs. The stored charge is in general around 20 µC for a 20 A thyristor. For a given device and its operating conditions, these characteristics are published in its specification sheet.

This inability of thyristors and TRIACs to switch at true zero crossings is responsible for power line spikes with high-frequency content. Spikes of over 4 V_{PP} are not unusual. In most commercial applications, this amplitude of spikes is inconsequential. However, some very sensitive electronic instruments may require significant suppression of such noise.

ZERO CROSSING

When the load contains a reactive element causing a phase lag, such as shown by the blue trace in Figure 3 (30° lag is shown), the zero-crossing noise becomes significantly worse as the SCRs and/or triacs turn on and off with additional delay. Just wiring itself can add a significant inductive component to an otherwise resistive load. Consequently, when tough EMI requirements are a part of the specification, the designer must be prepared to face the undesirable effects of the parasitic inductance and the phase lag. I observed 7 V_{PP} noise in a heating system consisting of a pure resistive, 10-kVA bifilarly wound heater, running at 220 V/400 Hz supplied by 10 m (30') of cable. The switching noise exceeded the allowed military levels of both conducted and radiated emissions between 60 and 200 kHz. Suppression of the noise at such power levels becomes quite a challenge, as any effective filter would be too large, too heavy and rather expensive. We'll discuss some solutions in Part 3 of thise article series.

Zero crossing switching is very useful in many applications. It can control power to the load by delivering AC bursts of energy, which is essentially a low speed pulse width modulation. The two limiting factors are the frequency of the AC power source and the time constant of the load. The commonly available 60 Hz power can be used with relatively slow devices only, such as electric heaters, some motors with sufficiently large inertia and similar devices. Zero crossing would be useless for light dimming because the light would be flickering. Controlling power at higher AC frequencies, such as 400 Hz or even 720 Hz commonly delivered by variable frequency generators by thyristors or TRIACs, is limited by those devices' high frequency capability.

MORE TO COME

In Part 3 I'll continue to review zero crossing switching as well as other more exotic SCR-based devices. I'll also discuss the use of other non-SCR types of power switches, such as MOSFETs and IGBTs, often used in control systems' power converters.

ABOUT THE AUTHOR

George Novacek is a professional engineer with a degree in Cybernetics and Closed-Loop Control. Now retired, he was most recently president of a multinational manufacturer for embedded control systems for aerospace applications. George wrote 26 feature articles for *Circuit Cellar* between 1999 and 2004. Contact him at gnovacek@nexicom.net with "Circuit Cellar"in the subject line.

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Zero Crossing Switching & Exotic SCR-Based Devices

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By George Novacek

Power switching at zero crossing is an efficient way to reduce switching transients. As I explained previously, exact zero crossing switching is impossible. Nevertheless, the resulting electromagnetic interference (EMI) is usually sufficiently low to be inconsequential in most situations.

Once I was involved with a project in which an electric heater belonging to a temperature control system was located in the vicinity of highly sensitive electronic systems. The bifilarly wound heater was almost a purely resistive load, but the cabling added some parasitic inductance. The pulse-width modulated (PWM) bursts of power ranged from 10 s up to continuous operation switched by thyristors. Unfortunately, the EMI performance was unacceptable.

While the temperature control worked perfectly, high-frequency noise generated by the switching exceeded the levels allowed by military standards CE03 (conducted emissions) and RE02 (radiated emissions).[1] A waiver to relax the limits had not been granted, and a filter was not an option because of its weight and cost. Eventually, a solution was accepted by the customer (see **Figure 1** and **Photo 1**).

Once the first thyristor fired after the zero crossing at the beginning of the power burst, relay K1 was energized through a metal-oxide semiconductor field effect transistor (MOSFET) Q3. At the end of the power burst, relay K1 was de-energized just before the last zero crossing turned the thyristor off. By-passing the thyristors during the bursts prevented the noise from being generated.

Because relays reaction time is typically 30 ms, K1 must close after the thyristors fire and open before the thyristors do. With some tweaking of the timing, only short noise spikes remained at the beginning and the end of the power bursts. These were accepted by the system integrator. As a cost reduction benefit, plastic-encapsulated thyristors could be used and forced air cooling was no longer needed. Because the relay was opening and closing while the thyristors were conducting, only about 6 V appeared across its contacts and no arcing occurred.

A Zener diode D1 replaced the usual freewheeling diode. Regular diodes prolong the collapse of the relay coil's magnetic field and this increases its dropout time significantly. A solution comprising an 80-V Zener diode and the 200-V MOSFET Q3 resulted in great reduction of the dropout delay.

Using modern power MOSFETs or insulated gate bipolar transistors (IGBT) instead of the SCRs would have likely resulted in acceptable emission levels without the need for the relay. Unfortunately, suitable MOSFETs or IGBTs were not available at the time. A typical

application of MOSFETs (or IGBTs) to switch AC power is shown by a simplified diagram in **Figure 2**. The switches are driven to saturation, while the output power is once again PWM controlled. For safety reasons, when the load requires more than about 48 V, you should use an optocoupler or some other means to isolate the control circuits from the high-power ones. Diodes D1, D2, resistor R2 and capacitor C1 generate 5-to-10-V DC to drive the MOSFETs' gates through resistor R1.

Our review of silicon-controlled rectifiers (SCR) would be incomplete without mentioning the Gate Turn-Off (GTO) switch. The GTO is a SCR which can be turned on by a positive pulse and subsequently turned off by a much greater negative pulse on its gate. **Figure 3** is the GTO schematic symbol. The GTO's four-junction structure is identical to that of a regular thyristor. However, its cathode is constructed such that the GTO can be viewed as a large number of individual thyristors on a common substrate.

Developed years ago by General Electric, the GTO is now offered by companies such as Westcode, Matsushita, Powerex, and others. GTO applications lay primarily with high-power industrial devices, such as locomotives, heavy machinery, and so forth. GTOs are generally rated for hundreds of volts and amps. In one typical industrial application, a GTO triggers 4,500 V/6,000 A at a di/dt rate of 2,000 A/µs.

Solid-state devices such as bipolar transistors, MOSFETs, and IGBTs can be used to switch rectified DC as is illustrated in **Figure 4a**, often smoothed out by a storage capacitor. While some loads, such as incandescent lights or heaters can be driven by the rectified half-waves without the storage capacitor, the use of smooth DC allows for much faster PWM than the mains frequency would have otherwise permitted. Typical of such applications are drivers of brushless DC

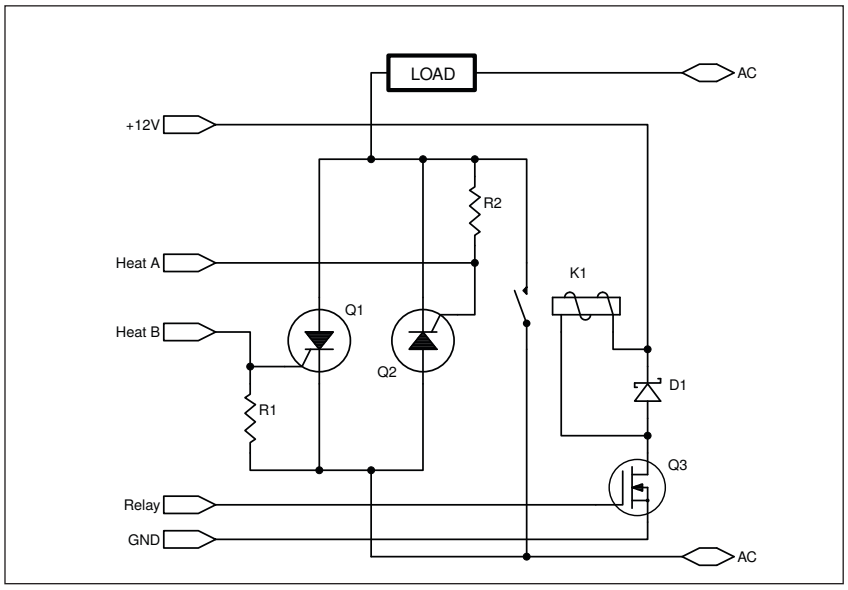

FIGURE 1
Simplified diagram of the solution to the excessive conducted and radiated emissions

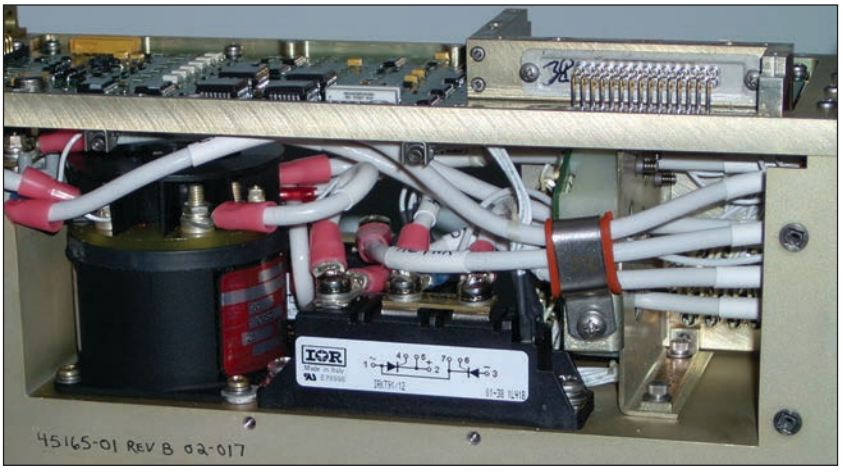

PHOTO 1
Back-to-back thyristor with a relay to the left

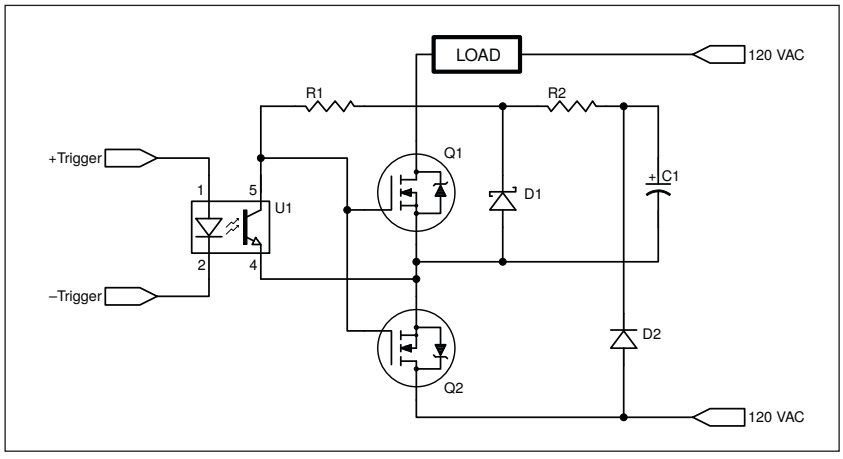

FIGURE 2
Using MOSFETs to drive an AC load

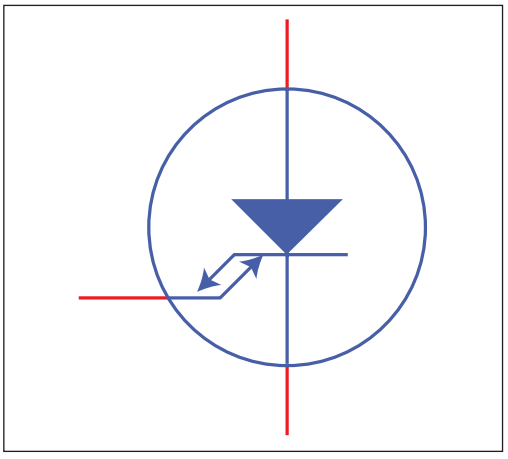

FIGURE 3
Gate Turn-off (GTO) thyristor

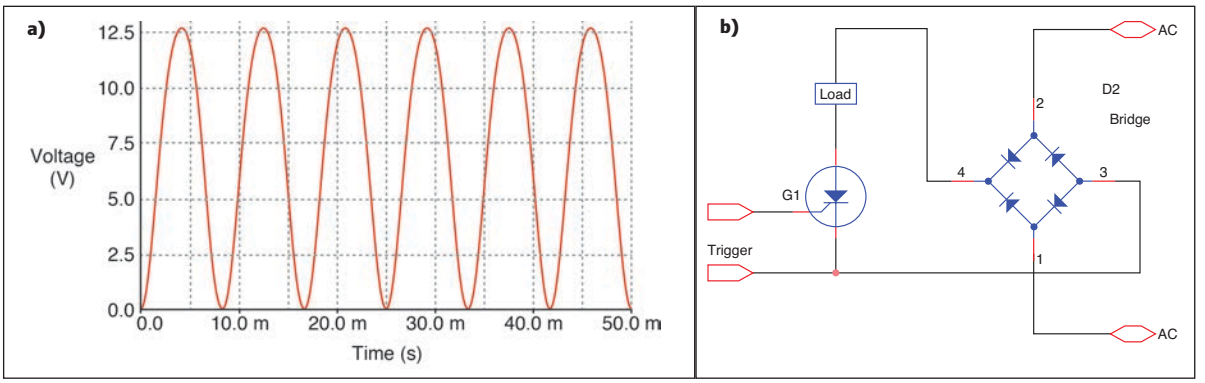

FIGURE 4
Waveform supplied to the power switch **(a)** and a typical application for a DC type load **(b)**

motors (BLDC), switching power supplies, and so forth. Figure 4b depicts a typical DC PWM control of a load. G1, in this case a SCR, can be replaced with other solid state devices with an appropriate trigger signal. The good old bipolar transistors can be used in this circuit, but transistors are driven by current, which, in power applications, may have to be up to 20% of the collector current. This can be improved by Darlington topology. In some applications, namely with inductive loads, power transistors require a snubber to significantly reduce the dV/dt switching speed. Because of these shortcomings power transistors are not as commonly used anymore, being substituted by MOSFETs or IGBTs. Load switches, such as those made by Texas Instruments, Toshiba, and others include many features discrete designs usually don't, such as protection and monitoring. The same applies to other common drivers, such as H and half-H when provided as integrated circuits.

Linear amplifiers are sometimes needed for control of some loads, but their efficiency is low and a lot of heat needs to be dissipated as compared with switching devices. It is often possible to use other methods, typically a PWM, instead.

Bipolar transistor shortcomings are alleviated by the IGBT, comprising a complementary pair of bipolar transistors (PNP and NPN) driven by a MOS FET. IGBTs exhibit very fast switching speed with dV/dt in the order of 5,000 to 10,000 V/µs; therefore, they usually do not require a snubber.

Power MOSFET was derived from the Field Effect Transistor (FET), also called Junction FET or JFET. JFETs can switch low voltage AC because their drain and source electrodes are interchangeable. JFETs are the core of analog switches, but their ratings are limited to about 40 V and a few tens of milliamps of current.

Power MOSFETs exist in four variations: N-channel enhancement, N-channel depletion, P-channel enhancement and P-channel depletion. N-channel enhancement type is the most common for power switching. Many present day MOSFETs need only 3-to-5-V gate voltage to be saturated. For switching applications, MOSFETs' drain-to-source resistance R_{DSON} is a crucial parameter. It is measured in milliohms. However, at high operating currents the drain to source saturation voltage may be higher than that

ABOUT THE AUTHOR

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circuitcellar.com/ccmaterials

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of bipolar transistors or thyristors. In these cases, an IGBT can provide better results. Reverse polarity diode may have to be added.

The trailing-edge dimmer mentioned in Part 2 works by turning the voltage off at some point on the wave in contrast to the leading-edge dimmer. Its waveform is shown in **Figure 5**. The circuit is similar to the one in Figure 2. Switching is accomplished by driving MOSFETs with appropriate logic. The resulting voltage across the load, just as with the leading-edge dimmers, is an average. This type of a dimmer is required for dimming CFL and LED lights.

There are also several rather exotic devices, such as Integrated Gate Commutated Thyristor, which is essentially a GTO with much higher sensitivity for the turn off. Injection Enhanced Gate Transistor (IEGT) is very similar to the IGBT but with much lower forward voltage drop. The MOS Controlled Thyristor (MCT) combines the load characteristics of a thyristor with the control characteristics of the MOSFET. The Static Induction Transistor (SIT) is normally on; it's turned off by a negative voltage on the base. It is a very fast switch working up to the microwave range. Static Induction Thyristor operates similarly to the GTO but is also capable of working up to the microwave region. Unless you work in a specific power field, it is unlikely for you to run into any of these devices. For further study, there is much information to be found on the Internet.

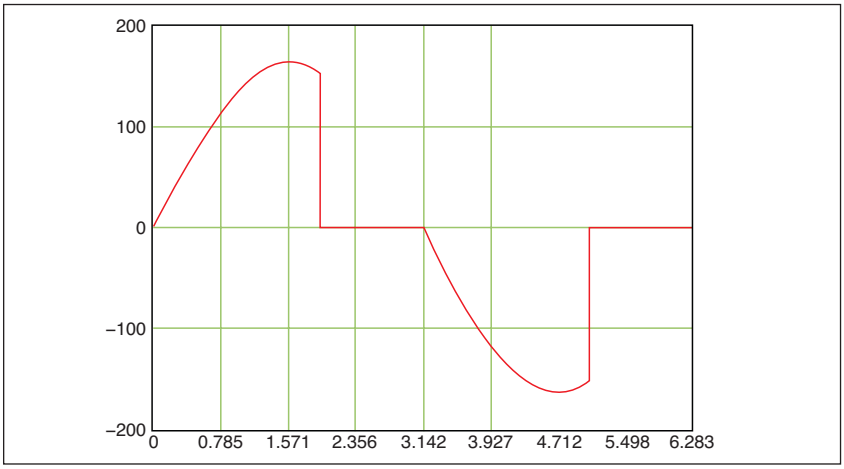
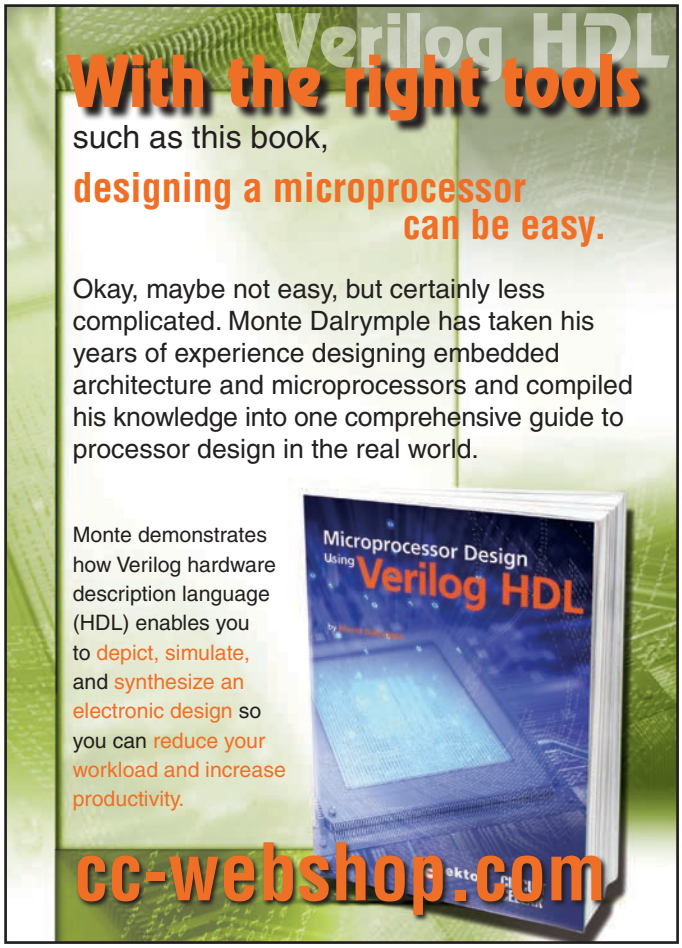


FIGURE 5
Trailing-edge dimmer waveform

So why did we spend so much time discussing power converters? As I mentioned at the beginning of this series, power converters are an important part of automatic control systems. And that's precisely what we'll focus on in the upcoming issues.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